Panel Discussions on Total Solar Irradiance Variations and the Maunder Minimum

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1. Measurements and models Of total solar irradiance

1,]. Summary of the results on irradiance variations: J .M. Pap and R. C. Willson, JPL

For more than a decade, total solar irradiance has been monitored from several satellites, namely the Nimbus-7, Scalar Maximum Mission (SMM), the NASA ERBS, NOAA9 and NOAA1O, EURECA, and the Upper Atmospheric Research Satellite (UARS) (e.g. Willson and Hudson, 1991; Hoyt et al., 1992; Mecherikunnel et al., 1988; Romero et al., 1993). These observations have revealed variations in total irradiance ranging from minutes to the 1 l-year solar cycle (Figure 1, from Frohlich 1993). The very small, rapid irradiance fl uctuations are due to solar oscillations (Woodard and Hudson, 1983; Frohlich, 1992). The short-term variations (from days to months) are directly related to the evolution of active regions via the combined effect of dark sun spots and bright faculae (Chapman, 1 987). The most important discovery of irradian ce observations is the 0, 1% peak-to-peak variation in total solar irradiance over the solar cycle (Willson and Hudson, 199]). This solzLr-cycle-rclzLtcd variation of total irradiance is attributed to the changing emission of bright magnetic elements, including faculae and the magnetic network (Foukal and Lean 1988). This solar cycle variability may also be related to changes in the photospheric temperature; however it is not clear as yet whether this change can be linked to the bright network component (Kuhn et al., 1988).

Although considerable information exists about the variations in total solar irradiance, the underlying physical mechanisms, especially that of its long-term variations, arc not well understood as yet. Furthermore, several theories for explaining the re-radiation mechanism of the missing energy in the sunspot-related irradiance dips have been put forward. One p articular part Of the theories suggests that the reduced radiation results in storage of the Mocked heat flux as thermal and potential energy of the convection zone around a spot, and this energy is re-radiated over the long radiative relaxation time of the layers effected by the spot (Foukal, 1981; Spruit, 1982a,b; Foukal

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et al., 1983; Spruit, 1993). Recent numerical convection models of energy and material

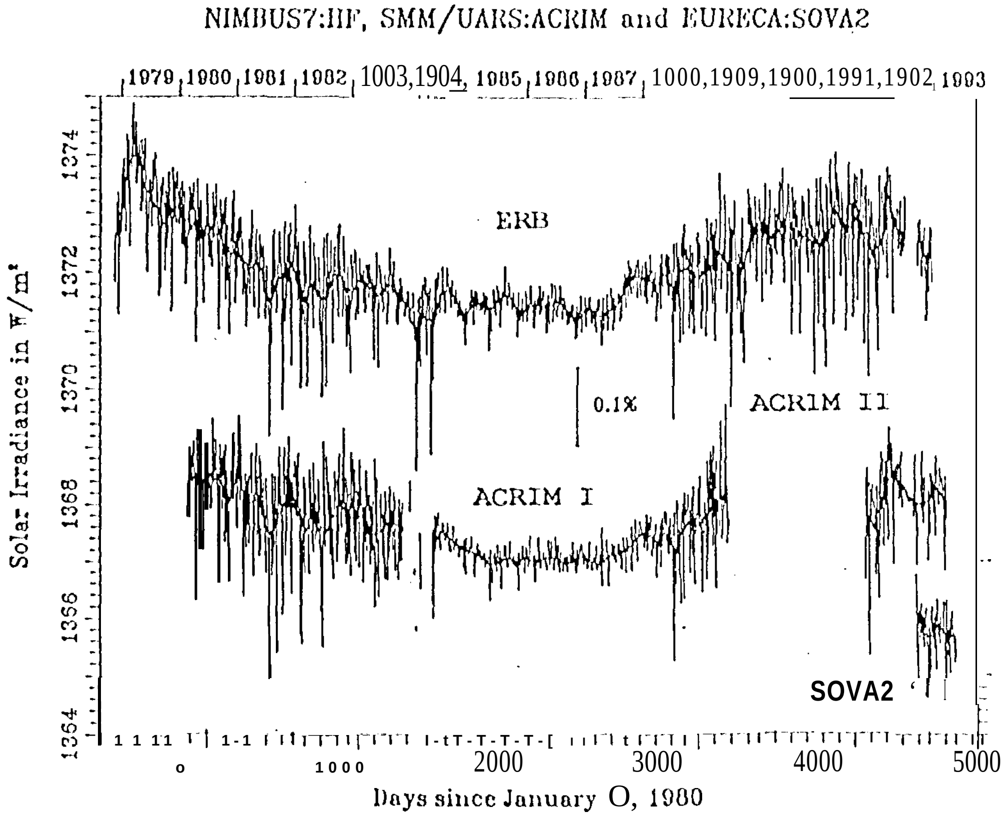

Fig. 1. Observations of total solar irradiance by the Nimbus-7/ERB, SMM/ACRIM I, UARS/ACRIM II, and EURECA/SOVA2 radiometers are plotted.

flowing around a sunspot do not indicate long-term storage of the heat flux, but show that most of the heat flux blocked by sunspot-like objects (magnetic perturbations) reappears at the surface, although some fraction of the blocked flux is carried horizontally far from the object (Fox et al., 1992; Fox and Sofia, 1993). Another explanation suggests that the energy blocked by sunspots is stored in the magnetic fields of the spots, in which case sunspots should cause dips in total irradiance during the early stage of their development (Wilson) 1981), as it is shown by some of the statistical analyses (Pap, 1985; Frohlich and Pap, 1989). A slow down flow is also supposed around the spots during their growing phase that is capable of transporting the blocked energy to surrounding regions where it emerges as facular enhancement (Schatten et al., 1986). Some calculation indicates that the facular excess flux can compensate the spot deficit on active regions time scale (Chapman, 1987).

],2, History of irradiance observations: R.C. Willson and J, M. Pap, JPL

Since the radiative output of the Sun is the main driver of the physical processes within the Earth's atmosphere, the precise and continuous determination of the value of total solar irradiance and its variation is extremely important. There are indications that changes in the solar energy output influence the Earth)s climate on time scales ranging from the Gleissberg cycle (Reid, 1987; Friis-Christensen and Lassen, 1991) up to the Maunder type of climate anomalies (Lean et al,, 1992). Furthermore, it is shown that persistent variations in total solar irradiance (as small as 0.5%) over a century could have explained a wide range Of climatic changes that occurred in the past (Eddy, 1977), Therefore, one of the main questions to be addressed is:

What do we need to achieve lol]g-term high precision irradiance database for climatic studies?

The first attempts to detect variations in total solar irradiance started as early as the beginning of this century. The first continuous observational program of total solar irradiance was performed at the Smithsonian Institution over the first half of the 20th century (Abbot, 1925; Hoyt, 1979). During the following 30 years, experiments with the same objective were conducted using aircraft, high altitude balloons, sounding rockets, and space flight platforms (Frohlich, 197 6). All these experiments were unable to detect variati on s in total irradiance that were unambiguously solar in origin. On the one hand, the intra- atmospheric experiments were highly effected by the selective absorption of the terrestrial atmosphere that masked solar induced irradiance variations from even nigh flying aircraft and balloons, On the other hand, failure of extra-atmospheric experiments on rockets and early satellites was due to the lack of sufficient radiometric accuracy.

Significant development in radiometry in the late sixties led to the development of the electrically self-calibrat,il]g active cavity irradiance detectors at different institutions: at the Jet Propulsion Laboratory (Willson, 1984), Eppley laboratory (l lickey and Karoli, 1974), World Radiation Center at Davos, Switzerland (Brusa and Frohlich, 1972), and at the Royal Meteorological Institute of Belgium (Crommelynck, 1'373). These new radiometers are capable of measuring total solar irradiance with an absolute accura cy Of + /-0. 2%. The developm ient Of these new type Of radi ometers and loxl~-term flight opportunities from space led to the discovery of changes in total irradiance related to solar activity.

The first long-term solar irradiance monitoring experiment was the Earth Radiati on Budget (ERB) on the Nimbus-7 sat ellit e that provided irradiance database from late 1978 to early 1993 (Kyle et al., 1993). The Nimbus-7/ERB experiment was followed by the ACRIM I and ACRIM II on aboard the Solar Maximum Mission (SMM) and Upper Atmospheric Research Satellite (UARS), respectively (Willson, 1993); and by the SOVA1 and SOVA2 experiments on EURECA (Crommelynck et al,, 1993, Romero et al., 1993). The demonstration that these experiments (ERB, ACRIM I and II, SOVA1 and SOVA2) showed the large excursions due to passage of large sunspots across the center of the Sun's disk convinced the skeptics that the darkening effects of sunspots on the total irradiance had indeed been detected. Furthermore, combination of ERB, ACRIM I, and ACRIM II give the solar cycle amplitude of the irradiance change from 1978 to 1993, covering two solar maxima and one solar minimum. The different observations of total solar irradiance are summarized in Figure 2 (from Willson, 1993).

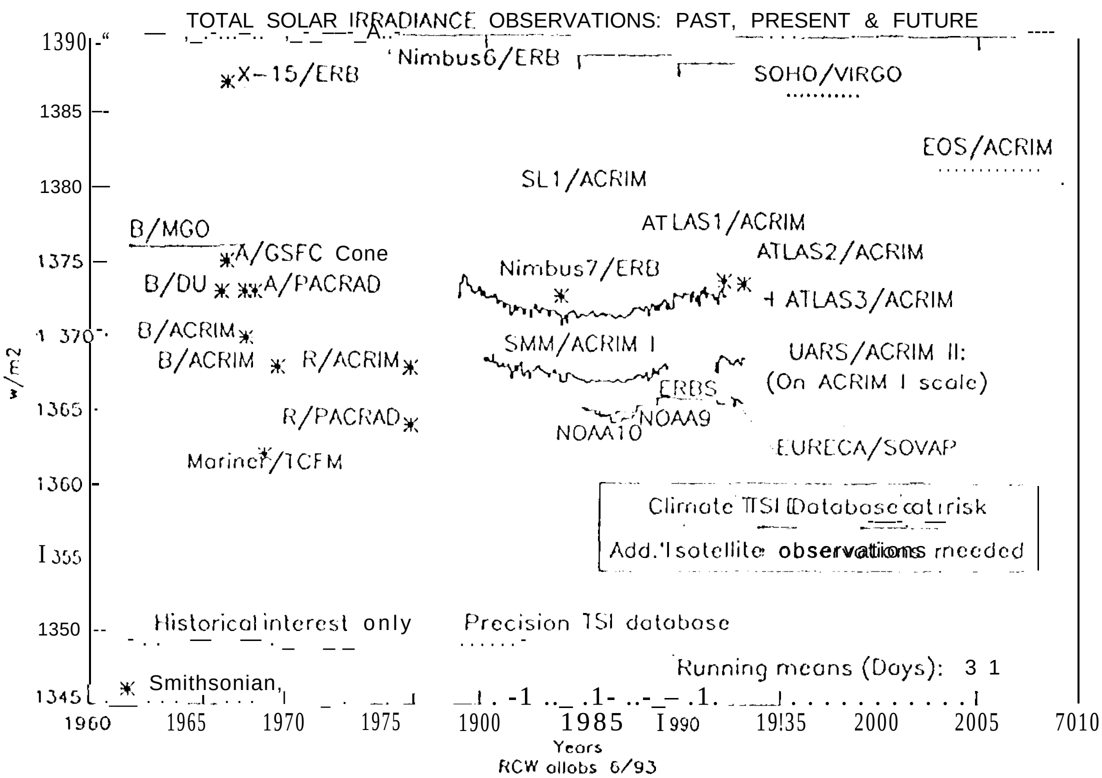

Fig. 2. Summary of the past and current irradiance observations is presented. Forthcoming irradiance observations of NASA and ESA are also indicated.

However, the current absolute accuracy of the operating active cavity radiometers (+/-0.2% SI) is still not adequate to provide long-term irradiance database for climatic studies, Therefore, the main goal is to build high-precision irradiance database that covers several solar cycles, For this purpose continuous observations of total solar irradiance with the same type of instrument with an overlapping strategy is needed to provide the maximum precision due to the smaller number of possible degrading variables. This approach can provide a long-term irradiance database with precision better than 50 ppm over decades that is sufficient to reveal variation as small as 0.5% over a cent ury.

Since the overlap requirement cannot always be achieved (e.g. failure Of satellites and/or lack of' flight opportunities), data sets gathered by different instruments should be used as a backup. For this purpose, extensive comparison of different flight instruments during the overlapping portion of their missions is required. In the case Of the gap between SMM/ACRIM I and UARS/ACRIM II data, their adjustment is achieved through their numerical intercomparisons with the Nimbus-7/ERB data. Systematic variations arising due to differing inherent responses and flight environments must be removed to make maximum quality comparisons. With these adjustments, the relationship between ACRIM I and ACRIM II should be established to better than 50 ppm (Willson, 1993).

A new type of radiometers: the cryogenic radiometers can achieve a higher accuracy than the operating active cavity radiometers (Martin and Fox, 1993). However, cryogenic radiometers operating near the temperature of liquid He (¡ 20 K) can provide an order Of magnitude smaller SI uncertainty ill the laboratory environm ent than ambient temperatûre devices. Their S1 uncertainty (probably not less than -| /- 200 ppm SI in flight experiments) is still above that required by the long-term climate data base. Further, the small apertures required, due to the need for power by the Stirling cycle He coolers, makes them much more vulnerable to contamination than larger ambient temperature radiometers. They may not provide the consistent measurement ability of ambient temperature instrumentation that facilitates the precision overlap capability.

1.3. Overview of the available surrogates for irradiance models: O.R. White, HAO

The detection of total irradiance variations by satellite-based experiments during the last 1 5 years stimulated modeling efforts to help identify their causes and to provide estimates of irradiance data for time intervals when no satellite observations exist. Since there is no adequate quantitative physical model for the variations in total solar irradiance, one has to rely on empirical irradiance models based on 'proxy' indicators of solar activity,

There are two basic sources of our measures of solar activity as far as solar irradiance is concerned: (1) Full diSk measurements of solar output, i, C., the Sun as a star (direct irradiance measurements), and (2) Images of the Sun showing the presence of dark sunspots, bright faculae, and bright network. Historically, images were used in

Wolf's and Schwabe's work first to define the solar cycle on the basis of sunspot counts. With the discovery of solar radio emission and development of methods for accurately measuring radiative energy from the Sun at radio wavelengths, we see Covington's use of the 10.7 cm radio flux in 1947 as a measure of activity on the Sun as a star. With the development of precision spectral photometers and solar magnetometers, several lollg-term experiments began in about 1975 to measure solar magnetic fields in the photosphere and chromospheric activity as shown by HeI, MgII, and CaII lines, The four principal full-disk radiometric indices are:

Type est. precision	Wavelength/line	Time Period	Measurement
Radio flux	10.7 cm	1947-1993	absolute flux 1 0/0
Spectral line	CaII K	1974-1993	dative flux 1%
Spectral line	HeI 10830	197s-1993	relative flux 2%(?)
Spectral line	MgII h&k	1978-1993	relative flux 2%(?)

1 stress that the line indices are chosen because these emissions show the bright structures associated with sunspots on the solar disk with much higher Contrast than ill the photospheric spectrum. This is precisely wily they are chosen as in di cators Of solar activity.

The principal indices derived from solar images arc the Zurich sunspot number, plage index, magnetic field index, and the photometric sunspot index (PSI). Each index has its own virtue of length of measurement, completeness, or precision. The magnetic and photometric sunspot indices are the only ones based on quantitative measurements of the solar magnetic field or sunspot size and brightness. The time series arc summarized as follows:

Type est. precision	Wavelength/line	Time Period	Measurement
sunspot no,	white light	1610-1993	sunspot counts ? '- - "
plage index	CaII 1<	1958-1987	area, intensity ?
magnetism	FeI lines	1975-1993	zeeman effect 15%
PSI	white light	1980-1993	Sunspot area, Contrast ?

With the advent of high quality electronic cameras, a new generati on of solar imaging experiments produce new indi ces for the facular excess - the bright features - and the sunspot deficit - the dark features - on the solar disk. These measures are photometric quantities usable directly in analysis of the sources of variability in total irradiance measurements, but they do not explicitly distinguish between individual sunspots and plages on the visible solar disk. The analysis is statistical and requires very stable image recording through the full optical train.

The source of these new types of measures is as follows:

Observatory	Wavelength/line period	observer time
San Fernando	CaII K & 6723A	Chapman 1990-1993
NSO (U. S.)	CaII K	Harvey 1992-1993
NAO(Japan)	5450,7770A	Nishikawa 1988-1989, 1992

The time base is still quite short because the technique is new, but these experiments are the basis for development of precision photometric telescopes in the U.S. SunRise program. Chapman (1993) shows that relative variations in the total irradiance can be recovered well for large sunspots that are easily identified. Early use of the statistical image analysis technique by both Chapman (1993) and Nishikawa (1993) also gives reasonable estimates of the relative variation of the total irradiance.

In addition to contemporary measurements, we have historical sets of solar spectroheliograms from Mt. Wilson Observatory, Meudon observatory) and Kodiakanal Observatory extending back to about 1910, Both the Mt. Wilson and Meudon images are being digitized and will be analyzed to give new sets of CaII K line data defining variability of plages over the last 80 years, The Meudon program is of particular interest since three wavelengths sampling three levels from the photosphere to the upper chromosphere, i.e., core and wing of the CaII K line and the core of the H] alpha line.

I emphasize that all of these ground-based measurements are narrow band or 'point' measurements in the solar spectrum from which we are trying to infer the area under the solar energy distribution curve as well as its shape. Furthermore, most of our available 'points) in the spectrum are spectral lines (CaII K, MgII k, HeI 108.3) or radio emission (10.7 cm) more sensitive to solar activity than the lower levels where the total solar irradiance originates.

The accuracy of our estimates of total solar irradiance is limited by the inaccuracy of the 'mapping spectral irradiances from these wavelengths to the total irradiance.

1.4. Summary of current irradiance models: J.M. Pap, JPL

Considerable effort has been made to combine the 15-year record of total solar irradiance from space with a variety of solar measurements more sensitive to solar activity in an effort to extend the absolute output record backward in time as far as is possible, However, the fundamental question is:

Whether the empirical models of total solar irradiance based on the described surrogates can reasonably predict solar irradiance changes with the long-term precision required by climatic studies?

On the one hand, the current empirical models of total irradiance, developed from various solar activity indices, such as the He-line equivalent width (Foukal and Lean, 1.988), several Fraunhofer-lines (Livingston et al., 1988), the 10.7 cm radio flux (Brandt et al., 1993; Frohlich, 1993), and the MgII h & k core-to-wing ratio (Pap et al., 1993), disagree significantly with the irradiance observations at the maximum of solar cycles 21 and 22 (Figure 3), Results of multivariate cross-spectral analysis show that considerable variation remains unexplained in total irradiance after removing the effect of sunspots and bright magnetic elements, and the residual variability changes with the phase of solar cycle (Pap and Frohlich, 1992; Figure 4).

The lack of agreement between the measured total irradiance and its model estimates from other full-disk solar indices is a current outstanding problem in the study of solar-cycle-related irradiance variability. One of the largest uncertainties in the irradiance models comes from the lack of knowledge of the effect of faculae, principally because of the lack of accurate long-term synoptic data. The full disk observations of faculae started only in 1988 by Nishikawa and recently by Chapman in 1990; however, these results are not yet incorporated into the irradiance models. On the other hand, previous studies have shown that besides the faculae, the magnetic network contributes to the changes in total irradiance, especially on long time scales (Foukal and Lean, 1 988; Willson and Hudson, 1988). It should be mentioned, however, that these new photometric observations do not include the bright magnetic network because of the difficulty of the precise measurement of its area.

Therefore, most of the irradiance variations related to the bright magnetic features (faculae and the magnetic network) are modeled by chromospheric surrogates such as the CaII K index, the full disk equi valent width of the He-line at 1083 nm, MgI I h & k core- to-wing ratio, and the 10.7 cm radio flux, although more than 90% of the total radiative flux of the Sun is emitted from the photosphere. However, the conversion factor between the area and intensity of photospheric and chromospheric plages is not known, the center-to-limb behavior of the contrast of white light faculae and that of the Ca K plages is quite different (Chapman et al., 1992; Schatten and Mayr, 1992). The

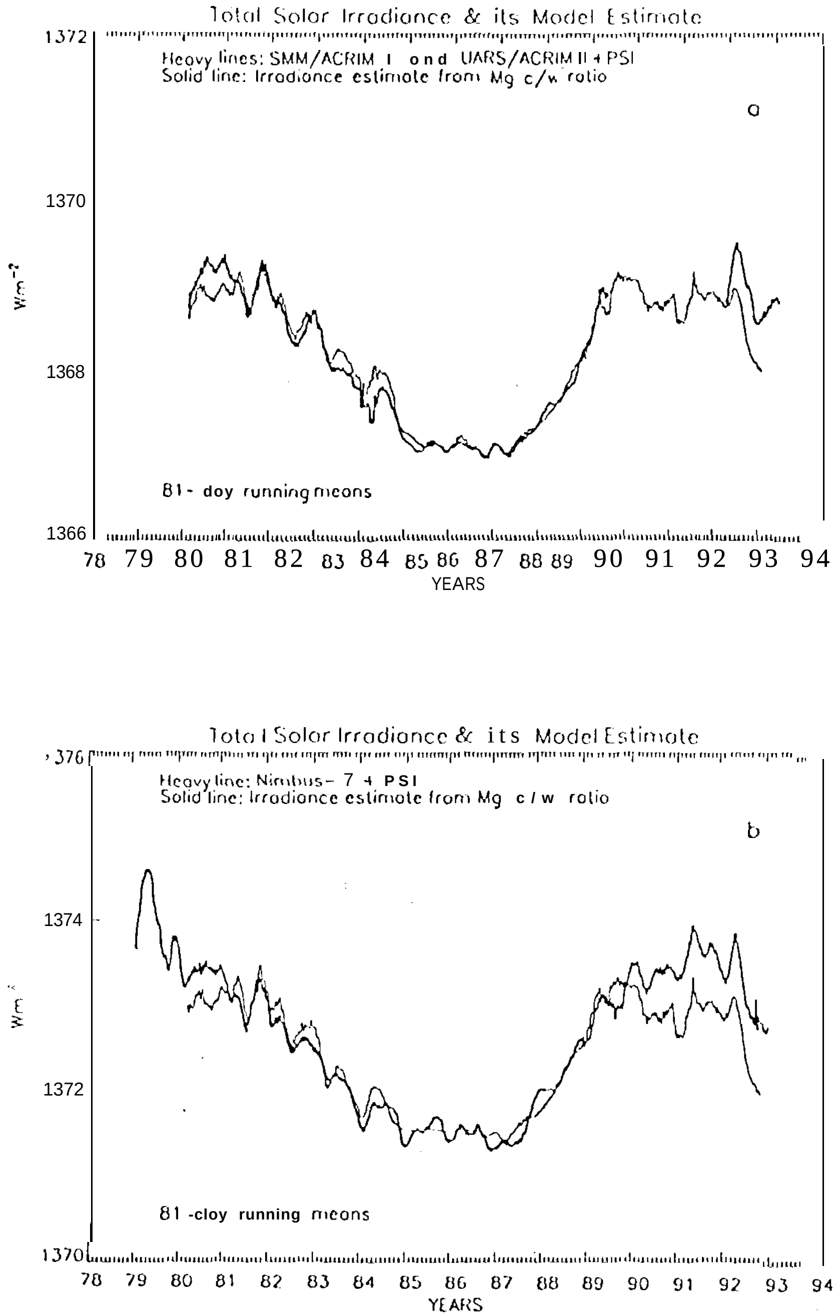

Fig. 3. The heavy lines show the 81-day running means of the Nimbus-7/ERB (a) as well as the SMM/ACRIM I and UARS/ACRIM II (b) total solar irradiance corrected for sunspot darkening. The solid lines represent the 81-day running means of the empirical model of total solar irradiance corrected for sunspot darkening.

current spatially resolved plage data set is combined from three different and incoherent data sets (obtained at the McMath Observatory from December 1970 until September, 1979, Mt. Wilson observatory from October 1979 to August 1982, and Big Bear Solar Observatory from September 1982 to November 1987); however, most modelers are not aware of this fact, Since the Big Bear data reduction ended in November of 1987 because of budget cuts, no intensity and area data of CaII K plages are measured and published on a routine basis (Marquette, 1992). Furthermore, it should also be mentioned that these plage data exclude the remnants of plages, which still cause a significant variation in both total and UV irradiances (Pap et al., 1991).

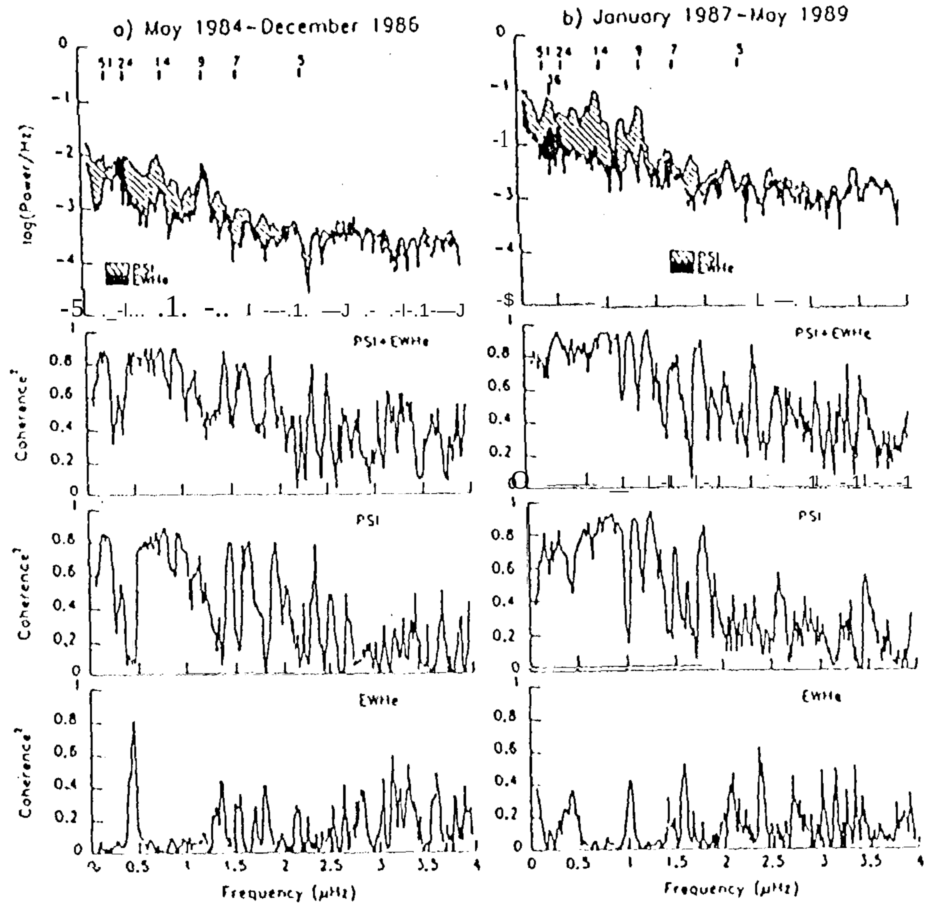

Fig. 4. The upper panels show the power spectra of the SMM/ACRIM I total solar irradiance for the time intervals of 1984-86 and 1987-89, respectively. The shaded areas give the portion of the ACRIM variance explained by the PSI and the He-line equivalent width at 1083 nm, respectively. The lower panels show the total and partial coherences squared.

Variability of the HeI equivalent width index and the 10,7 cm radio flux is rather complex: variation of both indices has a coronal contribution that is not present in the lower solar atmosphere where the total irradiance originates (Harvey, 1984; Tapping, 1987). While most Of the variation ill the HeI line equivalent width is related to plages, about 15% of its variability is related to dark filaments that do not effect total irradiance (Harvey and Livingston, 1993). This effect of filaments is also present in the indices derived from optically thick lines such as CaII K, MgI I k, and 11-alpha. Furthermore, it is not clear whether the irradiance effect of the quiet chromospheric network contributes the same as the plage-related variation of the HeI line (Harvey and Livingston, 1993). The 10.'7 cm radio flux has contributions from both free-free (bremsstrahlung) emissions (related to the weaker fields of plages and the network) and gyro resonance emission (related to the strong magnetic fields of sunspots). A more recent analysis suggests that the free-free contribution from the low chromosphere dominates its variability, except at the time of very high solar activity (Tapping, 1993). It should also be mentioned that the lack of good synoptic data sets for sunspots, especially during the last 15 years when high precision irradiance observations exist, introduce additional uncertainties into the irradiance models. The publication of high precision area and position of sunspots in the Greenwich Catalogue ended in 19'iG, Since then the sunspot observations are reported in the NOAA World Data Center Solar Geophysical D ata catalogue with much less precision. The current precision of the sunspot area measurements is 20-25% for large spots, but it can be as high as 50% for small spots (Sofia et al., 1982). Frohlich et al. (1993) have recently demonstrated that the irregularities in the sunspot area cause the largest uncertainty in the PSI. The results Of sunspot photometry ShOW that the contrast of sunspots depends on the area of sunspots (Steinegger et al., 1990; Chapman et al., 1992) and the current 1-'S1 model overestimates the sunspot, effect on total irradiance With about 40% (Brandt Ct al., 1990). Moreover, the change Of the contrast Of sunspots over the solar cycle (Maltby et al., 1986) is not taken into account in the irradiance models.

It has been shown that the evolution of active regions plays an important role in the changes of total irradiance (Willson, 1982; Pap, 1985; Frohlich and Pap, 1989). However, neither the evolution of sunspots or plages is taken into account in the current irradiance models; only mean values of contrast for these structures go into the regression calculations. No broad statistical study of the change of radiation from the sunspots and plages due to their evolution has been clone to give us the needed data to improve the empirical transformations. Full disk measures of solar activity, such as the He-line equivalent width, Mg core- to-wing ratio, and the 10.7 cm radio flux contain the evolutionary changes but in an undifferentiated form where sunspot, plage, and network contributions cannot be separated.

As has been described above, the principal sources of the total solar irradiance variability are known to be sunspots and bright faculae and plage regions. However, we still need to separate a quiet-Sun component from a chromospheric network component to account for the total amount of radiation from layers above the photosphere. Thus, there is the possibility of slow secular changes both in the network and globally in the Sun that remain unmeasured at this time. In addition to the unmeasured long-term changes, we also see the underestimate of total irradiance by surrogates of chromospheric origin at the times of solar maximum in the last two solar cycles.

We cannot assume that the difficulty lies in an instrumental problem: we must also consider that the empirical models fail at solar maximum because of a change in how the solar atmosphere responds to the presence of strong magnetic fields sustained over the 2-3 years of solar maximum. The empirical regression models derived from the full disk surrogates are controlled by the ascending and descending phases of the solar cycle and not by the mutual behavior of the various measurements during solar maximum. Thus, it may be that we simply do not have the same empirical transformations between total irradiance and surrogates such as CaII K, 10.7 cm, HeI 1083, and MgII h & k at solar maximum as during the periods when the emerging magnetic flux is both low and changing steadily at the beginning and end of a solar cycle.

Since the physics of the formation of the total irradiance and our common solar activity indices is not identical, our empirical models give only estimates with a precision of a few percent for the variability of the total solar irradiance due to both sunspots and faculae (plages). This inherent limitation of the current simple empirical models of total irradiance must be taken into account when irradiance models are used in climatic studies. Considering the significance of irradiance variations as a potential natural source of climatic changes, continuous observations of total irradiance from space are required to maintain a long-term, high precision irradiance database for climatic studies. In parallel with the direct irradiance observations, advanced theoretical and statistical studies are necessary to understand why, how and on what timescale the total radiative output of the Sun changes and thus, to reconstruct and predict the solar induced climatic changes.

1.5. Discussions led by J.M. Pap

Schlesinger: This is all very depressing. Do we really have to wait 50 years for the data to accumulate before we can answer this question of solar influence? Are there any simplifying insights or pivotal experiments that can be used to speed up our understanding of solar change and its effect in the atmosphere?

Parker: Given the complexity of both the solar atmosphere and the Earth's climate system, it will probably take 50 years to really understand how and why they vary as they do.

Schlesinger: Cannot wc clarify the existence of long-term irradiance changes from observations prior to the space observations?

Pap: The current absolute accuracy of radiometers is low (+/- 0,2$%), therefore individual measurements from the ground, balloons, aircraft, rockets, and from the space shuttle cannot reveal the small amplitude changes in total irradiance. in case of the measurements from the ground, balloons, and aircraft, the atmospheric effects cannot be neglected, the accuracy of these measurements is not better than 1%. Therefore, lollg-term, high precision irradiance observations from space with overlapping strategy arc needed to reveal the climatically significant irradiance changes.

Lean: It is not yet determined whether the discrepancy between irradiance observati on s and models is solar, rather than instrumental, effect, especially in the late seventies and in 19S0 considering the degradation of the instruments. Pap: The degradation of the SMM/ACRIM I instrument was 600 ppm over its 9.5 years of operational interval. The degradation of the radiometers are caused by the high energy solar fluxes, such as the UV and particle fluxes. Because of this, the ACRIM instruments contain till'cc radiometers: one of them measures the solar energy flux continuously, the second one once a month, and the third one is exposed to solar radiation only in every second or third month. With this operational mode, the change of total irradiance clue to the instrument degradation was corrected to a 50 ppm level. The difference between ACRIM I total irradiance and its model estimate in 19S0 was 300 ppm and it is well above the degradation level, Furthermore, the Nimbus-7/ERB instrument which started to operate in late November of 1978 showed the same trend as the ACRIM I instrument in 1980.

Frohlich: Furthermore, the degradation of the SOVA instrument on E URECA during the first month Of its operation was the same as that of the ACRIM I.

Hoyt: There is a discrepancy between the solar irradiance models and the Nimbus-7 measurements for 1979-1980 and 1987-1988. The measured irradiance is higher than the model values and modelers often ask what is wrong with the measurements. in order to force the measurements to match the model, the algorithm to reduce the counts to irradiances could be changed. Changes in the pointing, temperature sensitivity, elec tronic gain, or contamination could be made, but there is no experimental eviden ce to make the algorithm changes. Even if the changes could SC) I11C]1OW be made, the results after 1980 would probably be altered SUCh that a new model/measurement disagreement would occur. For 1987 and later, the Nimbus-7 radiometer was operating under increasingly favorable conditions as other platform instruments were turned off. Any differences then are even harder to explain by measurements problems.

Pap: It should be added that the UARS/ACRIM 11 total solar irradiance is also well above the irradiance estimates computed from our standard surrogates at the maximum of solar cycle 22, This difference strongly suggests that irradiance values cannot be estimated accurately during solar maximum, Research at the U .S, National Solar Observatory and at the J et Propulsion Laboratory will determine if the magnetic activity during the maxima of both cycles 21 and 22 provides a mechanism to explain the difference. We should keep in mind that our common surrogates are radiations formed in atmospheric layers higher than the photosphere where more than 90°% of total irradiance is emitted. Therefore, these indices represent different physical conditions than in the photosphere. Because of the lack of a physical theory to describe the radiation emitted by different solar structures, we are unable to map radiative losses from higher layers to those lower down accurately and, thus, explain the difference between observation and our current empirical models.

Livingston: The observations at the He I line at 1083 nm were essentially performed to study coronal holes. It has been a surprise that the correlation between the variations in the He-line equivalent width and total as well as UV irradiances is so good.

White: "1'0 improve the surrogates used in the irradiance models, digitization of different features (sunspots, faculae, network) is needed from a new set of CaII K images and magnetograms. As a further step, computation of the solar spectral energy distribution is necessary, taking into account the new photometric results from Chapman and Harvey using image analysis.

11. Solar Output in The Maunder Minimum: O.R. White, HAO

a. How well do we know the Sun's output in the Maunder Minimum?

We have three methods for estimating the Sun's total irradiance in the Maunder Minimum: 1) decrease in solar energy required for the amount cooling in the terrestrial atmosphere in the 17th century, 2) extrapolation of empirical models back in time, and 3) estimates from stars in a 'Maunder Minimum' state. The estimate of the decrease of irradiance from contemporary values ranges from ().20/0 to 0.7% With a consensus value at about 0.3% .

Discussion led by O.R. White

Schlesinger: What is the range of variation in the solar input do we have to consider realistically?

White: Zero to 1 percent in the radiative output. This estimate allows for factor of 2X on both the low and high side of current estimates from extrapolation of the regression formula back 300 years, The statistical realities in this extrapolation are horrible because we go well outside the fitted range. I also included the low values obtained from the analysis of solar-type stars (Baliunas, et al,, 1993) in this guess as well as the bias to the high side from Damon's early climate model analysis (Jirikowic and Damon, 1993). Other sources for estimates of the solar output in the Maunder Minimum are Lean, et al. (1992), Nesme-Ribes and Manganey (1992), Nesme-Ribes, et al. (1'393), and Hoyt and Schatten (1993).

Concerning the plasma output, we have information on the variability of the plasma output of the Sun; but have little notion of how it may couple to the lower atmosphere and cause sensible changes, Geomagnetic activity shows a steady increase over the last fifty years, and this reflects both the level of activity in the solar wind and variability of Earth)s magnetosphere. Radionucleide data clearly show variation in cosmic ray flux caused by changes in the output of solar plasma over the last seven thousand years. These data show characteristic periodicities of 208, 88, and 11 years. Conversion of these radioisotope variabilities to sources and properties of the solar wind and transient plasma ejections has not been done; therefore, the detailed connection to activity as measured by sunspot occurrence remains in a qualitative state at this time.

Frohlich: It should also be kept in mind that the correlation between total irradiance and its surrogates depends on the phase of the solar cycle, Models give different results for different phases of solar cycle since the value of the slope and intercept calculated from linear regression changes with the time during the solar cycle, even on yearly time scale, How do we know what is the right value of the intercept and slope when we extend the models back to the] 7th century?

Lean: Current irradiance models extended back to the time of the Maunder Minimum use the a,b linear regression coefficients determined from the decreasing phase of solar cycle 21.

White: One basic limitation in the current extrapolations is the lack of data covering many solar cycles: the data used in these estimates covers only two solar maxima and one solar minimum, at Lest. As such, the regression formulae describe only the 'strength' of two recent solar activity cycles and not any long- term variation in its zero point, i.e., variability of the quiet stellar atmosphere undisturbed by emergence of strong magnetic fields at the visible surface.

b. Did the Maunder Minimum really occur?

This point is now moot because of the careful work of Dr. Ribes and her colleagues in the study of the Paris Observatory archive for the period from 1640 to 1720. This study of the daily observations by Picard, La Hire, Cassini, and their successors clearly establishes the basic character of the solar cycle in the period from AD I 645 to AD1715, within which no sunspots were recorded during extended periods despite regular daily observation, Ribes and Nesme-Ribes (1 993), Ribes, et al. (1987), and Nesme-Ribes, et al. (1 989) give details of this analysis of the Paris Observatory archive. In particular, between AD1690 and AD I 702 only one spot was observed while an average of about 15 daily observations per month were recorded. This work gives the solar theorist a quantitative description of the rate and location of magnetic flux emergence and the change in solar rotation rate during this unique episode of solar history, Continued examination of the historical record only strengthens the original arguments made by Eddy (1976) for the existence and importance of the Maunder Minimum episode, Its identification in the 10Be and 14C paleoclimate records points to similar occurrences in the past and suggests its reality as a naturally occurring irregularity in the cyclic variation of stars of the same age and mass as the sun.

Discussion:

White: Hoyt's current re-examination of the quality of sunspot observations from 1610 to the present shows that the Maunder Minimum period was well covered by other observers throughout western Europe. A lack of solar observations did occur in the mid 18th century, well after the resumption of the solar cycle in AD171 O (see the Hoyt and Schatten paper at this meeting),

c. What are the implications for the solar dynamo?

Clearly the hLck of sunspots for several decades and their occurrence in a narrow latitude band near the solar equator (about -1-/-18 deg latitude) is an extremum that has to be allowed by a credible dynamo model. More important may be the observation that between 1660 and 1710 almost all of the sunspots emerged in the southern solar hemisphere. The apparent increase in the degree of differential rotation on the Sun also gives another observational constraint to the theory.

Discussion:

White : Throughout this workshop, several collc.agues (Nesme-Ribes, Krause, Sokoloff, Kremliovsky) mentioned the potential importance of 'mixed parity' dynamos in understanding the occurrence of sunspots in only one solar hemisphere. See Sokoloff and Nesme-Ribes (1993) and papers given at this workshop by these colleagues. Periods of large N-S a.symmetry correspond to times of minimum total magnetic energy produced by the a]pha-omega dynamo described by Brandenburg, Krause, and Tuominen (1989, Turbulence and Nonlinear Dynamics, (Meneguzzi, et al. editors)),

White: We have to ask whether the toroidal solar dynamo operating at low latitudes actually ceased generating magnetic field during this time , or were conditions in the torus and the convection zone such that flux tubes did not rise to the visible Sul'face of the sun?

d. Did the Maunder Minimum really contribute to the Little Ice Age?

Since the Maunder Minimum lasts only about 70 years, the question arises about its causal influence in the 300 year Little Ice Age, which lasted from AD1 550 to AD1850. In his discussion, Bradley cautions not to oversimplify the Little Ice Age as a global phenomena involving only the mean temperature or glacial advance. Our view is biased by the picture in Europe where the most complete records exist, These indicate that this local climate was much harsher than today, a condition which did not apply worldwide, He also points out the need to consider the change in volcanic activity and aerosol production throughout this period and into the 20th century as another major factor in climate modulation.

Discussion:

Ribes: The deepest part of the Maunder Minimum corresponded to periods of extreme low temperature in Western Europe.

Parker: The Maunder Minimum was not the only solar excursion in this period. Both the Dalton and Sporer Minima occurred in this time interval, i.e., at AD1 800 and AD1 500, respectively.

c. What about solar influence in the Medieval Warm Epoch (AD1 000-A D1250)?

Discussion:

White: Is there any question about the occurrence of the Medieval Warm Epoch?

Bradley: In the report of the workshop devoted to this period, Malcolm Hughes concludes that the moderated climate observed in western Europe and eastern North America may not have occurred on a global scale. Thus, it is not possible to judge that the mean global temperature increased significantly.

White: in the 14C and 10Be time series shown at this meeting, 1 notice that none of them yet extend earlier than about AD1 500. Is there ally doubt about the so-called 'Grand Maximum" of solar activity in the period from AD I 100 to AD 1300 in the radionucleide record?

Raisbeck: 'The earlier data arc available: wc did not show them because the analysis is not complete. Yes, the Grand Maxi mum is present in our new time series.

White: 'I'his period is the example of a 'positive' extremum in solar output as opposed to the 'negative' extrema shown by Maunder Minima episodes of very low solar activity, Although the Maunder Minima episodes appear to be easier to identify and, therefore, study as a isolated phenomenon; the positive extrema should not be ignored. The 10Be level today is approaching the high levels seen in the 12th century as pointed out by Jirikowic and Damon (1993); therefore, characteristics of the AD I 100-AD1300 period may indicate the direction of climate forcing by the sLm when the level of solar activity remains high for many decades. However, Bradley's caution at this meeting about the Little Ice Age also applies here, i.e., wc may not be dealing with a global changes described simply by, say, the mean global temperature or a single forcing function strong enough to drive the mean climate state above the natural variability of the Earth's atmosphere.

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Figure Captions:

Fig. 1. Observations of total solar irradiance by the Nimbus- 7/ERB , SMM/ACRIM I, UARS/ACRIM II, and EURECA/SOVA2 radiometers are plotted.

Fig. 2, Summary of the past and current irradiance observations is presented. Forthcoming irradiance observations of NASA and ESA are also indicated.

Fig. 3. The upper panels show the power spectra of the SMM/ACRIM 1 total solar irradiance for the time intervals of 1984-86 and 1987-89, respectively. The shaded areas give the portion of the ACRIM variance explained by the PSI and the He-line equivalent width at 1083 nm, respectively. The lower panels show the total and partial coherences squared,

Fig. 4, The heavy lines show the 81-day running means of the Nimbus-7/ERB (a) as well as the SMM/ACRIM I and UARS/ACRIM II (b) total solar irradiance corrected for sunspot darkening. The solid lines represent the 81-day running means of the empirical model of total solar irradiance corrected for sunspot darkening.